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X-ray Emission from Stephan's Quintet  
and Other Compact Groups

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Abstract

A search for X-ray emission from five compact groups of galaxies with the Einstein Observatory revealed detections from three groups. Soft, extended X-ray emission was observed in Stephan's Quintet which is most likely caused by hot intracluster gas. This provides evidence for dynamical interaction among the group galaxies. X-ray emission from the group Arp 330 may also originate in hot intracluster gas. Stephan's Quintet and Arp 330 have the largest velocity dispersions among the groups studied suggesting a correlation between high velocity and the release (or properties) of hot gas. X-ray emission from Arp 318 may originate in its member galaxies.

## I. Introduction

The X-ray emission detected from rich clusters of galaxies reveals a hot metal-enriched intracluster medium (ICM) that probably originated from processed gas swept-out of galaxies. This provides direct evidence for the occurrence of interactions among cluster galaxies. Since dynamical interactions depend on the galaxy (and/or ICM) density, they are expected to be important in the groups of highest known galaxy density, such as Stephan's Quintet. While the high galaxy densities suggest a short crossing-time and a strong dynamical interaction, the existence of numerous compact groups, each having a significant spiral fraction has provoked controversy regarding the reality of the compact groups, their age, and their state of dynamical evolution. We have searched for X-ray emission from five compact groups to try to find a hot ICM in these systems. Our measurements provide evidence for dynamical interaction in some of these groups.

## II. Optical and Radio Properties

The compact groups we studied are listed in Table 1A, together with their redshift, velocity dispersion, central position, and the radius encompassing the group's apparent bright members (Hickson 1982; Arp 1966). The groups contain all their apparent bright members (4 to 6 galaxies each) within a projected radius of 30 to 100 kpc (i.e., comparable to the size of a single large galaxy!)

The area centered on Stephan's Quintet (SQ) contains five galaxies within a 60 kpc radius ( $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ), four of which are group members. The bright galaxy NGC 7320, with a redshift velocity of  $763 \text{ km s}^{-1}$ , is a foreground galaxy. The SQ group itself includes NGC 7317, 7318a, 7318b, 7319, and, about 5' east, also NGC 7320C (which is  $\sim 2$  mag. fainter). Other, fainter members may be present at larger separations (Zwicky, et al. 1961; Lynds 1972). While the group galaxies are not very bright ( $\sim L^*$ ), the central galaxy density is at least an order of magnitude larger than that of most rich clusters. The pair of galaxies NGC 7318a/b appear, on photographic plates, to be "interacting", with

peculiar spiral-arm-like features extending from both galaxies. The line-of-sight velocity difference between the two galaxies is large ( $\sim 900 \text{ km s}^{-1}$ ).

Radio observations of SQ reveal both HI and continuum emission. Three velocity systems of HI are seen (Shostak et al. 1983), with the bulk of the HI emission lying outside the optical galaxies. The SQ galaxies have no substantial amount of HI in their disks (possibly due to galaxy encounters). The radio continuum emission (van der Hulst and Rots 1981) forms a ridge between NGC 7318 and 7319, which partly coincides with the spiral-arm-like optical regions in NGC 7318b and suggests an interaction between NGC 7318b and an ICM.

The other groups have been studied in less detail than SQ. A318 contains the galaxies NGC 833, 835, 838, 839, and 848. The group velocity dispersion is small:  $\sim 90 \text{ km s}^{-1}$ . (All velocities are from the Second Reference Catalog, and/or from Sargent (unpublished).) Bright emission lines have been observed from the nuclei of all five galaxies (de-Vaucouleurs et al. 1976). Four of the galaxies are spirals (some peculiar) and one is a peculiar SO. The group A330 is a "chain" of 6 galaxies (1 spiral, 1 SO, and 4 ellipticals, some peculiar) with a velocity dispersion of  $\sim 500 \text{ km s}^{-1}$ . Zwicky et al. 1961 classify the region as a medium-compact cluster, with A330 at its center. The groups A321 and A327 contain 5 and 4 galaxies, with small velocity dispersions (Table 1A).

### III. X-ray Observations and Results

The five groups were observed with the Imaging Proportional Counter of the Einstein Observatory (see Giacconi et al. 1979 and Gorenstein et al. 1981). The observed fields, dates, and exposure times are summarized in Table 1A. X-ray maps of the detected groups are presented in Figure 1.

X-ray Luminosities. X-ray emission was detected from A318, A319 (Stephan's Quintet), and A330. Upper-limits were obtained for A321 and A327. The X-ray properties of the detected sources are summarized in Table 1B, including: the position of the peak X-ray intensity; the radius  $r_x$  around the peak that

encompasses the  $2\sigma$  intensity level of the smoothed contours; the net counts within  $r_x$  in the 0.5-3 keV energy band (corrected for a background count derived from an outlying annulus); the X-ray flux and luminosity (corrected for Galactic absorption); the parameters for a thermal spectrum and a power-law ( $S_x \propto \nu^{-\alpha}$ ) fit; and the Heiles (1975) value for the galactic column density  $N_H$ .  $3\sigma$  upper-limits to the X-ray emission from A321 and A327 were obtained from the net counts within 150 kpc radius of the group center. In all three detections, the source intensity is  $\geq 5\sigma$  and consistent with the group position. The detected 0.5-3 keV luminosities range from  $2 \times 10^{41}$  to  $3 \times 10^{42} \text{ ergs s}^{-1}$ . The SQ 0.1-3 keV luminosity is  $5 \times 10^{42} \text{ erg s}^{-1}$ ,  $\sim 10$  times stronger, and much softer, than expected from all the individual galaxies emission (§IV). An X-ray contour map superimposed on an optical map of SQ is shown in Figure 2. The luminosity of A330 is also considerably stronger (factor of  $\sim 20$ ) than the group's expected galaxy emission.

Spectral Analysis. The total net counts from the Stephan's Quintet source is  $62 \pm 14$ . 50 of the 62 counts fall in the low-energy ( $\leq 1$  keV) channels (and 32 counts are below 0.5 keV), showing that the source is very soft. X-ray spectra of late-type galaxies generally show a much smaller fraction of their emission in these low energy bands (e.g., Fabbiano et al. 1982). Fitting the 8 energy channels and 2 variables ( $N_H$ , and the spectral parameter) yields, for SQ,  $N_H = 8 \times 10^{20} \text{ cm}^{-2}$  (similar to the Heiles 1975 value derived from HI data), and a best-fit temperature (using an exponential + Gaunt factor fit) of  $kT = 0.4 \pm 0.2 \text{ keV}$  (i.e.,  $T = 5 \times 10^6 \text{ K}$ ). Alternatively, a power-law fit yields a steep power-law index of  $\approx 3$ .

The A318 and A330 sources do not show similarly soft spectra; most of their counts ( $\geq 90\%$ ) are in the  $\geq 0.5$  keV range. The best-fit temperatures (with large uncertainties) are 5 keV for A318 (with a  $1\sigma$  lower-limit at 1.5 keV), and  $\geq 2$  keV for A330 (with a  $1\sigma$  lower-limit at 1 keV).

Angular Size. The detected sources appear to be marginally resolved; the IPC point-response-function has a HWHM of  $0.8'$  in the high energy channels and  $1.1'$  at low energies. The observed radial distribution of the net flux in SQ was compared with that of the point source 3C273, in both the hard ( $> 0.5$  keV) and soft ( $< 0.5$  keV) energy channels. The profiles were fit to both a Gaussian and a Lorentzian distribution (the latter resembles a King profile). In all cases, i.e., Gaussian and Lorentzian fits, hard and soft emission, the source in SQ appears more extended than 3C273. For example, in the hard energy band the best-fit Lorentzian core-radius is  $1' \pm 0.2'$  for SQ, versus  $0.3' \pm 0.01'$  for 3C273 (although 3C273 does not fit well a Lorentzian profile). Similar extensions are observed in the other two sources (which appear less symmetric; Fig. 1).

#### IV. Discussion

Stephan's Quintet. The arguments indicating that the X-ray emission from SQ originates in a hot intracluster medium are given below. 1) The luminosity of  $10^{42}$  ergs  $s^{-1}$  (or  $5 \times 10^{42}$  ergs  $s^{-1}$  at 0.1-3 keV), is higher than is usual for galactic emission from the five galaxies combined. 2) The emission is soft ( $\sim 5 \times 10^6$  °K), unlike the emission from galaxies. 3) The emission appears extended. 4) The centroid of emission is consistent with the group center.

We used a second-order least-squares fit to the observed (Long and van Speybroeck 1983)  $L_X$ - $L_{opt}$  relation for galaxies in order to assign an expected X-ray luminosity to each of the five galaxies (including the foreground galaxy). The X-ray emission expected from any single galaxy in SQ ( $\leq 10^{41}$  ergs  $s^{-1}$ ) is over an order of magnitude fainter than observed here. The combined emission from all five galaxies has an expected luminosity (0.5 - 3 keV) of  $3.5 \pm 0.4 \times 10^{41}$  ergs  $s^{-1}$ , i.e., at least three times weaker (or ten times in the 0.1-3 keV band) than observed. The SQ emission is also much softer, and more extended, than expected from the galaxies. It is therefore unlikely that most of the emission originates in the SQ galaxies.

NGC 7319 is classified as a Seyfert 2 galaxy (Huchra et al. 1982). X-ray observations of Seyfert 2 galaxies (Kriss et al. 1980; Kriss 1980) yield numerous upper limits that are lower than the SQ luminosity. Of the six Seyfert 2 galaxies detected in X-rays, five are in the range  $2$  to  $8 \times 10^{41}$  ergs s<sup>-1</sup> (0.5-4.5 keV). Since NGC 7319 has low values of H $\beta$ /[OIII], and H $\beta$  FWZI, its X-ray emission is expected to be low (Kriss et al., 1980). Moreover, the X-ray centroid position is displaced from NGC 7319 by  $\sim 1.5'$  ( $\sim 2\sigma$  of IPC uncertainty). It is thus unlikely that most of the emission originates in NGC 7319.

The pair of apparently interacting galaxies NGC 7318a/b is near the X-ray centroid. While normal galactic emission from these galaxies is unlikely to contribute significantly to the observed  $10^{42}$  ergs s<sup>-1</sup>, hot gas released from the galaxies could account for part of the emission. Another interacting pair, the Antennae (NGC 4038/39), has similar soft X-ray emission (Fabbiano and Trinchieri 1983). This softness is an unusual feature in normal or peculiar late type galaxies (e.g., Fabbiano et al. 1982). The Antennae emission was interpreted by the authors to include a soft component from hot gas between the galaxies. However, the Antennae has a lower luminosity ( $7.7 \times 10^{40}$  ergs s<sup>-1</sup>) than observed here and a smaller size. If a significant part of the emission arises from NGC 7318 a/b, it most likely originates in hot gas swept out of the galaxies during an interaction.

The most likely origin of the emission is thus radiation from a hot ICM. This explanation is also consistent with an extension of the characteristics of X-ray emission observed in richer groups and clusters to the small but compact group observed here. Specifically, the luminosity of  $10^{42}$  ergs s<sup>-1</sup> is consistent with the  $L_x - N_{0.5}^c$  relation observed for groups and clusters (Bahcall, 1980). ( $N_{0.5}^c$  is the central galaxy density within 0.5 Mpc of the group center.) The low gas temperature is consistent with the relations between

T and the group velocity-dispersion and  $N_{0.5}^C$  (Mushotzky 1983). Several of the small Morgan groups (Morgan *et al.* 1975, Bahcall 1980, Kriss *et al.* 1983) have X-ray luminosities of 0.5 to  $1 \times 10^{42}$  ergs  $s^{-1}$ , and extensions of  $\leq 400$  kpc, similar to the source in SQ.

The central electron gas density required to produce the observed luminosity is estimated to be  $\sim 10^{-2}$   $cm^{-3}$  (assuming a flux profile  $S_X \propto (1+(r/r_c)^2)^{-1}$ ,  $r_c = 0.7' \approx 30$  kpc (see § III),  $kT = 0.4$  keV, and  $r \leq 150$  kpc). The total mass of the gas is highly uncertain since neither the gas volume nor its exact density profile are known. Assuming a uniform gas distribution within the core, the core mass is  $M_c(\text{gas}) \approx 3 \times 10^{10} M_\odot$ . The cooling time of this gas — is of order  $10^8$  years; the hot gas must therefore be younger than this time scale. (The HI clouds in SQ may be cool remnants of previous encounters.) The central gas pressure is  $\sim 10^{-11}$  dyne  $cm^{-2}$ ; this is sufficient to confine the weak radio continuum ridge in SQ (§ II). The X-ray centroid is coincident with the position of the radio ridge and the arm-like optical structure extending from NGC 7318b. Both may result from dynamical interaction of the galaxy with other members and/or the ICM.

A318. The X-ray source in A318 has a luminosity of  $2 \times 10^{41}$  ergs  $s^{-1}$  and is centered (within the IPC uncertainty) on the central galaxy NGC 838; this galaxy is the most active emission-line member in the group. The source appears to be extended in the direction of the other bright galaxies (Figure 1). Unlike SQ, the emission from A318 is not soft; the spectrum is consistent with that observed in galaxies. The observed luminosity is also consistent with that expected from the group galaxies as estimated from the  $L_X - L_{opt}$  relation. The velocity dispersion of the group ( $\sim 90$  km  $s^{-1}$ ) is too small in comparison with the high temperature ( $6 \times 10^7$  K) implied by the X-ray emission. It is thus likely that most of the X-ray emission from A318 originates in the galaxies themselves.

A330. The X-ray emission from A330, at  $3 \times 10^{42}$  ergs s<sup>-1</sup>, is 20 times stronger than the total galaxy emission expected in the group. The source is extended, and its peak position is consistent with the location of the bright galaxy. The emission is not especially soft; the estimated temperature is  $\geq 2$  keV, with a  $1\sigma$  lower limit of 1.5 keV. This temperature, however, especially in the softer range, is not inconsistent with the relatively large velocity dispersion of the group (using the observed  $T - \sigma_v$  relation with its large scatter; Mushotzky 1983). A330 is located at the center of a medium-compact nearby Zwicky cluster, and may thus represent a compact core of a larger cluster. The observed X-ray properties of the source, i.e., its  $L_x$ , extent and temperature, combined with its optical properties and velocity dispersion, suggest that the source may originate from a hot ICM. The emission characteristics are consistent, within the observed scatter, with the optical-X-ray correlations (such as  $N_{0.5}^C$  or  $\sigma_v$  versus  $T$  or  $L_x$ ) observed for clusters and groups of galaxies.

#### V. Summary

X-ray emission is detected from three compact groups of galaxies and upper limits are found for two other compact groups. The X-ray emission from Stephan's Quintet and A330 probably originate in hot intracluster gas. The observed X-ray luminosities, extensions, and temperatures are consistent with extrapolations of the properties of richer groups and clusters. These two groups exhibit the largest velocity dispersions among the groups studied and the largest X-ray luminosities. The source detected in A318, with lower  $L_x$  and velocity dispersion, may be produced by the individual galaxies. The three groups with low velocity dispersions (A318, A321 and A327; the last two with measured X-ray upper limits) may have insufficient gas pressure to strip the gas from the galaxies and form a substantial hot intracluster medium.

The observed X-ray emission by hot gas in SQ and A330 constitutes the first

detection of such emission from compact groups of galaxies. The X-rays in this case provide direct evidence for dynamical interaction among the group galaxies.

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Table 1

## A. Compact Group Parameters

Group Name		z	$\sigma_r(v)$ km s <sup>-1</sup>	R group <sup>(a)</sup>		$\alpha, \delta$ (1950) Group Center <sup>(b)</sup>	X-ray obs. Date	Exposure Time (net)
Arp no.	Hickson; Other			arcmin	kpc			
A318	H16; NGC838	0.013	90	3.2	75	02 <sup>h</sup> 07 <sup>m</sup> 06 <sup>s</sup> -10°23.9'	1980 Jan 22	3217 <sup>s</sup>
A319	H92; Stephan Q.	0.021	400	1.6	60	22 33 43 +33 42.4	1980 Dec 28	2880 <sup>s</sup>
A321	H40	0.021	170	0.9	32	09 36 24 -04 37.5	1980 Mar 06	2536 <sup>s</sup>
A327	H34; NGC1875	0.030	140	0.6	32	05 19 06 +06 37.7	1981 Feb 16	2955 <sup>s</sup>
A330	---	0.029	500	(1.9)	(96)	16 48 02 +53 29.3	1980 Apr 12	1234 <sup>s</sup>

## B. X-Ray Properties (0.5-3 keV)

Group Arp no.	$\alpha, \delta$ (1950) (X-ray peak)	$r_x$ <sup>(c)</sup>		$N_x$ net count	$F_x$ (10 <sup>-13</sup> ) erg cm <sup>-2</sup> s <sup>-1</sup>	$L_x$ (10 <sup>41</sup> ) erg s <sup>-1</sup>	kT <sup>(e)</sup> keV	$\alpha$	$N_H$ (10 <sup>20</sup> ) cm <sup>-2</sup>
		arcmin	kpc						
A318	02 <sup>h</sup> 07 <sup>m</sup> 09 <sup>s</sup> -10°22.8'	4'	90	26±12	3	2	5	0.5	2
A319	22 33 41 +33 42.1	4	150	30±10	5	10	0.4	3	8
				62±14 <sup>(d)</sup>	23 <sup>(d)</sup>	50 <sup>(d)</sup>			
A330	16 48 08 +53 30.5	5.4	280	40±12	9	30	>2	0.5	3
A321	09 36 24 -04 37.5 <sup>(b)</sup>	4	150	7±7	<2	<4			
A327	05 19 06 +06 37.7 <sup>(b)</sup>	2.8	150	8±6	<3	<10			

(a) Hickson's radius; contains the bright group members.

(b) Optical center of the group.

(c) Radius around peak within which the net source count and luminosity are determined. Flux and luminosity are corrected for Galactic absorption using  $N_H$ .

(d) For the 0.1-3 keV energy band.

(e) The 1 $\sigma$  lower-limit is 1.5 keV for A318 and 1 keV for A330. The 1 $\sigma$  upper-limit of SQ is 0.6 keV.

Figure 1. X-ray contours for the 3 fields with detected group sources. Maps correspond to the energy range 0.3 - 3.5 keV, with a Gaussian smoothing function of 1' HWHM. The average background is subtracted and vignetting corrections applied. Contour levels are (2, 4, 6, 8...)  $\sigma$  above background. The crosses represent the group galaxies. Thin lines indicate the positions of the rib shadows.

Figure 2. The X-ray contours for Stephan's Quintet superimposed on a deep IIIa-J photograph kindly supplied by H. Arp. The X-ray map was constructed with a Gaussian smoothing function of 1' HWHM and corresponds to the energy range 0.2 - 2.2 keV. Contour levels are at 20% (2  $\sigma$  above background), 30%, 50% (heavy contour), 70% and 90% of the peak brightness. The insert shows the 50% contour of 3C 273 with the same smoothing function and pulse height channels.

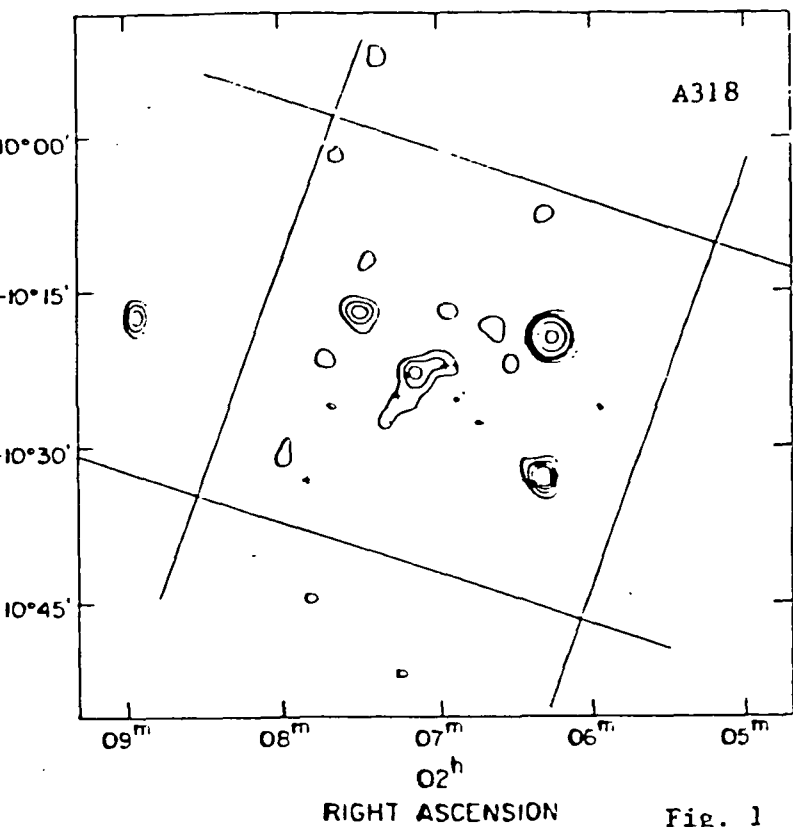


Fig. 1

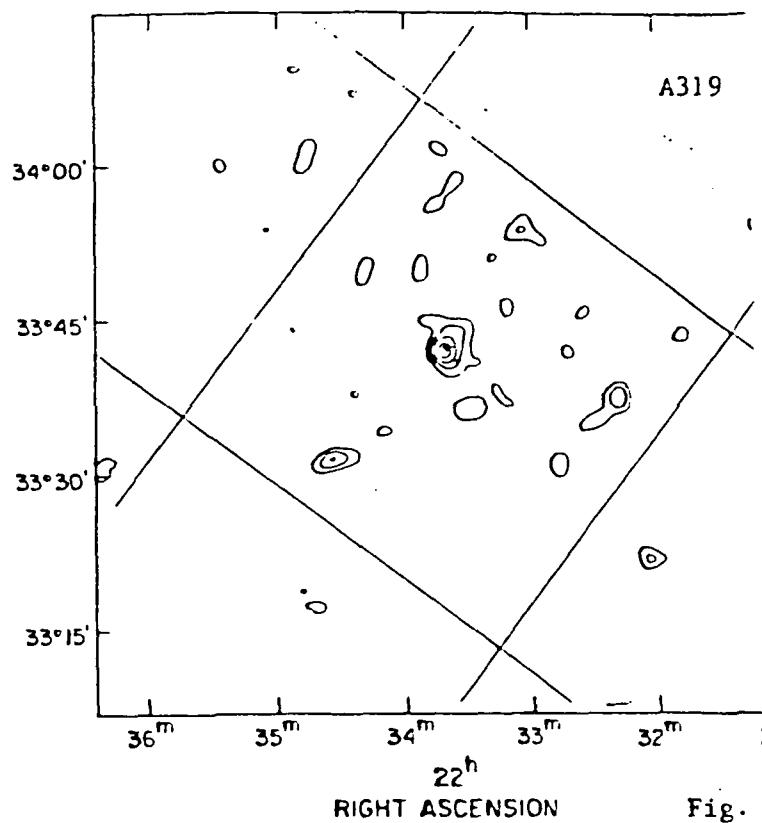


Fig.

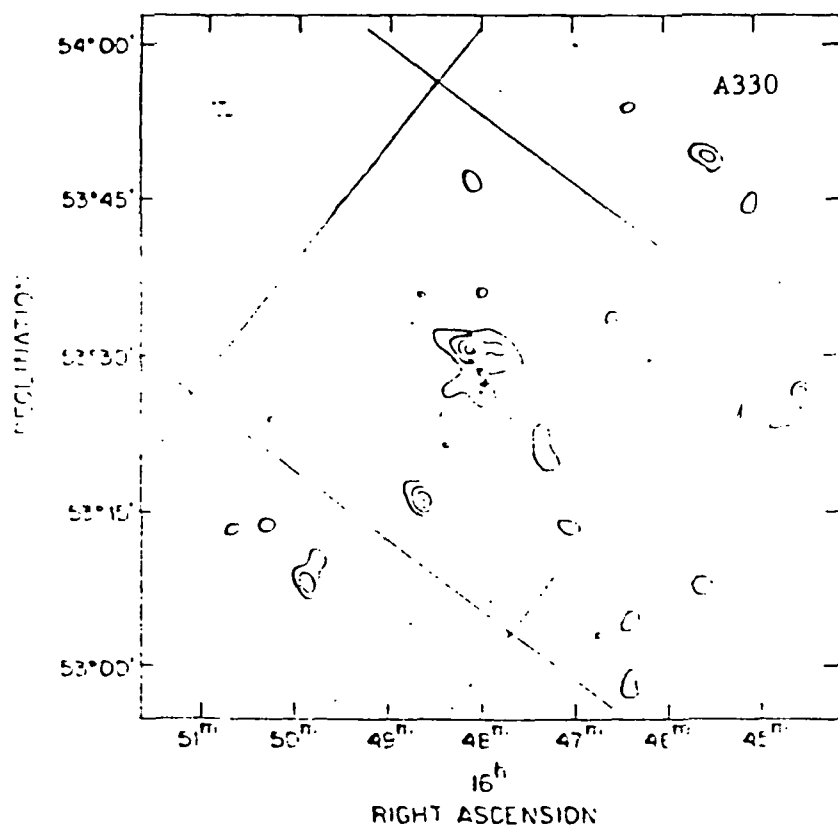


Fig. 1

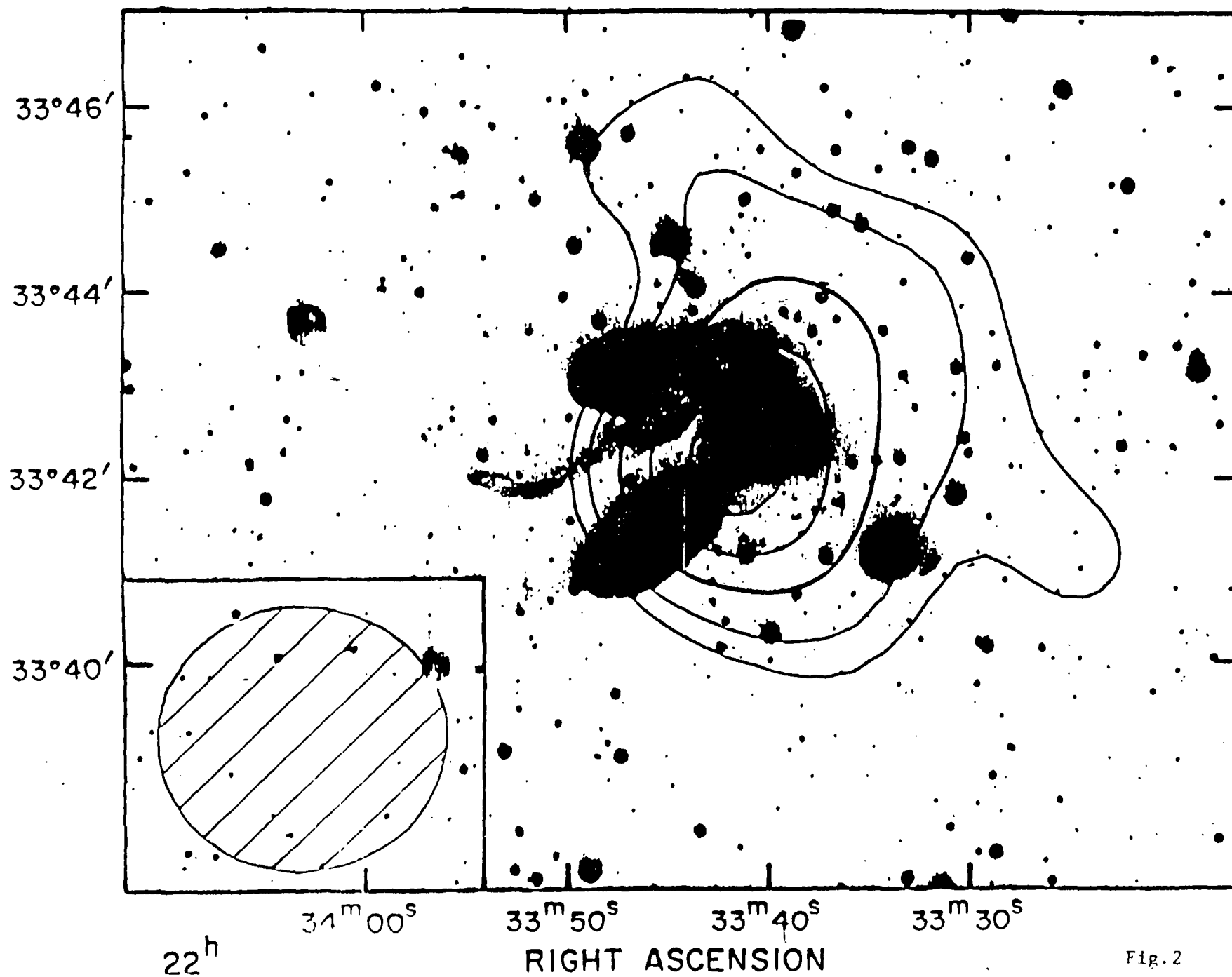


Fig. 2